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The impacts of land conversion and management measures on the grassland net primary productivity over the Loess Plateau, Northern China

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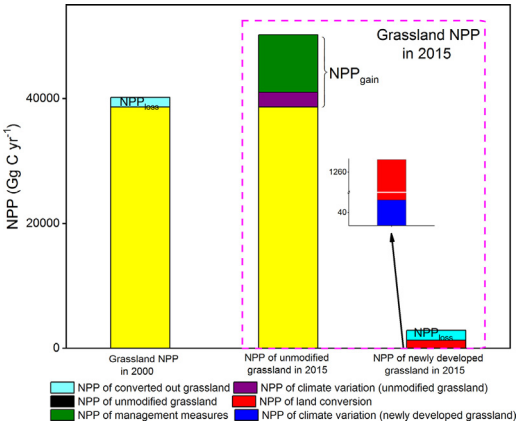
HIGHLIGHTS

- Human and climate factors contributed differently to grassland NPP increase.
- Roles of climate variation, land conversion and management measures were quantified.
- Land conversion added negative effects in grassland NPP increase.
- Management measures were the primary reason for grassland NPP increase.
- Climate variation showed positive impact in grassland NPP increase.

GRAPHICAL ABSTRACT



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ABSTRACT

In the 1990s, the Chinese government began implementation of a series of national-scale restoration programs to combat environmental degradation. As one of most important arid and semiarid regions of China, the Loess Plateau has attracted attention related to the effectiveness of these initiatives. The present study analyzed land use and cover change (LUCC) of the grassland in the Loess Plateau and the consequent change in net primary productivity (NPP) based on a consecutive land use data derived from the European Space Agency Climate Change Initiative land cover maps and the CASA (Carnegie-Ames-Stanford Approach) model driven by MODIS-NDVI data. The contributions of climate variation and human activities (including land conversion and management measures) to these changes were also quantitatively differentiated. The results indicated that the area of the Loess Plateau grassland experienced a net increase of 0.43×10^4 km^2 over the study period. The total NPP of the Loess Plateau grassland increased by 11,325.13 Gg C·yr^{-1}, of which the human activities and climate variation were responsible for 78.45% and 21.55%, respectively. The land conversion reduced the grassland NPP by 308.60 Gg C·yr^{-1}, whereas management measures increased the NPP by 9197.97 Gg C·yr^{-1} in the otherwise unmodified grassland. Overall, ecological restoration programs have effectively increased grassland NPP in the Loess Plateau. However, human activities played both positive and negative impacts in this process.

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1. Introduction

Land degradation is a global issue that has led to the deterioration of the structure, function, and services of ecosystem, while causing serious environmental problems (Gibbs and Salmon, 2015; Bai et al., 2008). It also seriously undermines the livelihood and food security of people, especially in the economically underprivileged regions (Le et al., 2016; Andersson et al., 2011). According to an assessment of the United Nations Food and Agriculture Organization, 61.40 million km^2 of land globally has suffered from degradation, and 26% is severely or very severely degraded (Gibbs and Salmon, 2015). Changes in land use are among the most important causes of land degradation; while land use and cover change (LUCC) has substantially altered the land surface (Pielke, 2005; Foley et al., 2005). Land degradation mostly occurs in arid and semiarid regions, where the vegetation is relatively vulnerable to anthropogenic and climatic disturbances (Yang, 2010). As one of the world's largest vegetation types, grassland ecosystems are mainly distributed in the arid and semiarid regions that contribute significantly to food security by providing meat, milk, and crops for human consumption (White et al., 2000; O'Mara, 2012). Therefore, grasslands have been deeply affected by both climate change and human activities.

China has 3.93 million km^2 of grassland, covering nearly 40% of the total land area. The spatial extent of China's grassland has changed substantially over the last half century as a result of the population growth and socio-economic development (Mu et al., 2013). The Loess Plateau, located in the arid and semiarid regions of northern China, serves as an important ecological barrier in China. A shortage of water resources causes the ecosystems in this region to be fragile and sensitive to climate change (Xie et al., 2016; Sun et al., 2015). In recent decades, the Loess Plateau has attracted considerable attention because of large-scale land degradation; specifically, overgrazing and land conversion are recognized as the primary driving forces of grassland degradation (Zhao et al., 2013; Fu and Chen, 2000).

To combat and mitigate the land degradation, the Chinese government has launched a series of national-scale ecological policies and programs during the late 1990s and early 2000s. The Grain for Green Project (GGP), defined as replacing croplands and grazing lands with trees and grass, is the most famous because of its massive scale, huge cost, and potentially enormous impacts (Wang et al., 2007). In 2003, another large ecological restoration program, the Grazing Withdrawal Program (GWP), was initiated to complement the effects of the GGP. The GWP particularly emphasizes on alleviating grazing pressure and restoring the degraded grassland through grazing exclusion, employing cultivated pastures, or other measurements in the western China (Zhang et al., 2016; Mu et al., 2013). Numerous research studies have been conducted to evaluate the ecological effects of these restoration programs since their implementation. The currently available studies have demonstrated that conditions related to the plant community, soil properties, and carbon sequestration have greatly improved (Zhou et al., 2011; Cheng et al., 2011; Zhao et al., 2013). The recovery of degraded vegetation also effectively reduced surface runoff (Zhang et al., 2007). Most of these studies focused on the field measurements or local scale observations. Although the monitoring of vegetation restoration using remote sensing has also been widely reported, they generally did not take the large-scale LUCC into account, and so fail to comprehensively reflect the actual situation on restored lands.

Net primary productivity (NPP), defined as the net amount of organic matter fixed by plants through photosynthesis, represents the net carbon flow from the atmosphere to the terrestrial ecosystems (Gang et al., 2015). NPP simulation models, such as climate-based models (e.g. Miami model (Lieth, 1977), Thornthwaite Memorial model (Lieth and Eas, 1972), process-based models (e.g. CENTURY (Parton et al., 1993), TEM (Mcguire et al., 1995), BIOME-BGC (Running and Hunt, 1993) as well as light use efficiency models [e.g. CASA (Potter et al., 1993); GLO-PEM (Prince, 1991)], have been widely reported at multiple levels during the recent decades. The process-based models are superior in local scale NPP estimation for the complicated parameters and processes incorporated. The light use efficiency models provide an alternative way in estimating the broader scale NPP due to the readily accessible parameters derived from satellite-based data. As one of the most important indicators of ecosystem function, NPP reflects the growth status of vegetation and the health of ecosystems. Therefore, NPP is usually used as an indicator of ecosystem function change resulting from land degradation or improved land management (Bai et al., 2008). It has also been widely used to distinguish the relative contributions of climate change and human activities to vegetation dynamics (Erb et al., 2009; Wang et al., 2016; Zhou et al., 2014). However, most of these studies have been based on the assumption that the land use types remained unchanged. In the ecological projects implemented regions, how the LUCC and land management measures have affected the spatial pattern and NPP of grassland, and how much climate variation contributes to these changes are still open questions; these areas of research need to be addressed.

Recognition of the LUCC of grassland and its effects on NPP, as well as the quantitative assessment of the related driving forces are essential for answering these questions. The present study primarily aims to: i) characterize the spatial pattern of LUCC in the Loess Plateau grassland by using a consecutive land cover maps from 2000 to 2015; ii) quantify the change in grassland NPP induced by LUCC during this period; and iii) to distinguish the relative contributions of climate variation and human activities (land conversion and management measures) to grassland NPP. The results of this study will not only provide baseline data for comprehensively assessing the efficiency of ecological restoration programs, but will help the land managers and policy makers to understand the current situation in restored grassland of the Loess Plateau, and develop future ecological policies related to managing grassland production in the western China.

2. Materials and methods

2.1. Study area

The Loess Plateau, located between 33°43′–41°16′ N and 100°54′–114°33′ E, covers an area of approximately 640,000 km^2 in the middle reaches of the Yellow River in the northern China (Fig. 1). An arid and semiarid climate dominates most of this region, with mean annual temperature (MAT) of 4.3–14.3 °C and precipitation (MAP) of 200–750 mm (Li et al., 2010; Guo et al., 2010). Highly erodible loess covers the surface of the Loess Plateau, with an average thickness of about 150 m (Liu, 1964).

The vegetation patterns in this region are characterized by a mosaic of agricultural vegetation, forests, and herbaceous plants. Grasslands, the dominant vegetation type, cover 42.86% of the total area. The grasslands stretch from the north, across the middle, and to the west of the Loess Plateau. Croplands are the second largest land use type, composing up to 35.57% of the total land cover, and are mainly located in the southeast portion of the Loess Plateau at relatively low elevations. Forests, mainly distributed along the Taihang, Lvliang, and Qinling Mountains, cover 18.35% of the total area of the Loess Plateau. Areas of urban, barren/deserts, and water/wetlands land use account for 1.57%, 1.62%, and 0.01% of the total area of the Loess Plateau, respectively. Land use and cover changes over time are mainly caused by human activities. The severe soil erosion currently observed in many areas was caused by long-term reclamation and climate change, factors that have had adverse impacts on the natural vegetation and the local environment. The Loess Plateau has been ranked as the most erodible area in the world (Zhang and Liu, 2005; Sun et al., 2015).

2.2. Data and processing

2.2.1. MODIS NDVI data

Moderate-resolution imaging spectroradiometer (MODIS) normalized difference vegetation index (NDVI) data with a 500-m spatial

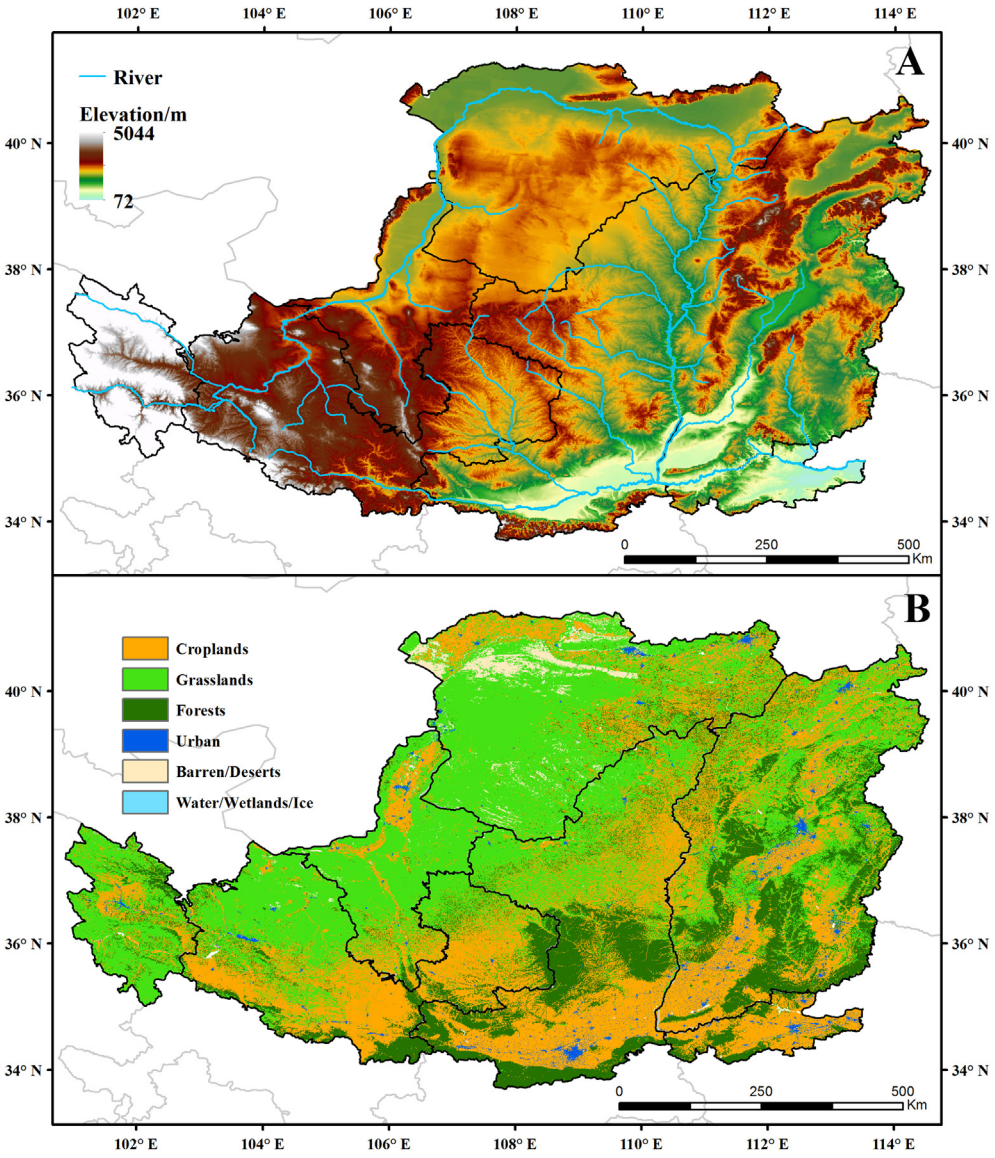

Fig. 1. The elevation (A) and land use types (B) of the Loess Plateau in 2015.

resolution between 2000 and 2015 were used in this study. These data were extracted from the MODIS product MOD13A1 by using the MODIS re-projection tool. The monthly NDVI data during the growing season (April–September) were generated from the 16-d NDVI data by the maximum-value composite method and then was reprojected to the Albers equal area projection and WGS84 datum. The NDVI data were then used as input data in the grassland NPP estimation model.

2.2.2. Land cover data

The European Space Agency Climate Change Initiative Land Cover (ESA CCI-LC) maps were used in the present study to generate the annual land cover map of the Loess Plateau that includes fourteen natural, five developed and mosaic, and three non-vegetated land classes (Bontemps et al., 2015; Duveiller et al., 2018). The overall accuracy of ESA CCI-LC data was estimated to be 71.7% globally. This dataset have been widely used in detecting the land use/land cover change worldwide (Kuppel et al., 2017; Li et al., 2017; Yang et al., 2017). The annual land cover maps of the Loess Plateau from 2000 to 2015 were used to evaluate LUCC and its effects on changes to grassland NPP.

2.2.3. Meteorological data

Meteorological data, including monthly average temperature, monthly precipitation, and solar radiation from 2000 to 2015, were used in this study. These data were obtained from the 72 meteorological stations in the Loess Plateau. These data, provided by the Meteorological Data Service Center of China, were interpolated using ANUSPLIN (version 4.2) to create regular monthly data layers with the spatial resolution same as NDVI data.

2.3. Methods

2.3.1. Estimation of actual NPP

The Carnegie-Ames-Stanford Approach (CASA) model, a light use efficiency model driven by remote sensing and meteorological data, was employed to calculate the actual NPP of grassland in the Loess Plateau (Potter et al., 1993; Field et al., 1995). The CASA model has been proved

to be superior in simulating carbon assimilation by plant growth in the Loess Plateau (Feng et al., 2013, 2016). In the CASA model, NPP is calculated based on two components: the absorbed photosynthetically active radiation (APAR) and the use efficiency (ε) of vegetation on APAR that reaches the surface, which is calculated as follows:

$$NPP_{act}(x,t) = APAR(x,t) \times \varepsilon(x,t) \quad (1)$$

where x is the spatial location (pixel number), and t is the time. $APAR(x, t)$ is the canopy-absorbed incident solar radiation of pixel x in time t ($MJ \cdot m^{-2}$), and $\varepsilon(x,t)$ represents the actual light-use efficiency ($g\ C \cdot MJ^{-1}$) of pixel x in time t. A detailed description of the algorithm can be found in Mu et al. (2013) and Zhu et al. (2007).

2.3.2. Estimation of potential NPP

The potential NPP of grassland, which was used to reflect the single effect of climate variation on grassland productivity in the Loess Plateau, was simulated by a synthetic model. This model was based on the actual evapotranspiration, which was closely related to the rate of photosynthetic of vegetation (Zhou et al., 1998). It was established mainly on the biomass data from 125 datasets related to natural mature forest in China and 23 datasets related to natural vegetation NPP including forest, grassland, and desert, and can be expressed as follows:

$$NPP_{po} = RDI^2 \times \frac{GSP \times \left(1 + RDI + RDI^2\right)}{(1 + RDI)\left(1 + RDI^2\right)} \times \exp\left[-\sqrt{(9.87 + 6.25RDI)}\right] \times 100 \quad (2)$$

$$RDI = \left(0.629 + 0.237\ PER - 0.00313\ PER^2\right)^2 \quad (3)$$

$$PER = PET/GSP = BT \times 58.93/GSP \quad (4)$$

where GSP is the precipitation during the growing season (mm), RDI is the radioactive dryness index which can be calculated by PER (rate of evapotranspiration), PET is the potential evapotranspiration (mm), and BT is the biological temperature, which is the average temperature during the vegetative growth of plants (0–30 °C, temperatures below 0 °C and above 30 °C are excluded). NPP was calculated in units of $g\ DW \cdot m^{-2} \cdot yr^{-1}$.

2.3.3. Validation of actual NPP and potential NPP

The modeled results of actual NPP and potential NPP were verified with the field survey observed data from August 2010 and 2011. The field observation data contains the typical steppe and the desert steppe, which are the main grassland types in the Loess Plateau. The detailed geographical information of experiment sites were presented in Table 1. The validation results exhibited reliable estimation accuracy, indicating that the CASA model is suitable for estimating the NPP of grassland in the Loess Plateau ($R^2 = 0.817$, $P < 0.001$) (Fig. 2A).

The observation data used for validation the potential NPP were from the grazing enclosure sites or from areas that have barely experienced disturbance by humans. These experiment sites were located in the typical steppe grassland in Guyuan and desert grassland from Yanchi. These sites were considered to be affected only by climate variation, and the natural communities of grassland ecosystems. The validation results indicated that the synthetic model satisfactorily estimated the potential NPP of grassland of the Loess Plateau ($R^2 = 0.734$, $P < 0.01$) (Fig. 2B).

2.3.4. Analyze of the trends of climate factors and NPP

The ordinary least square estimation was calculated for each pixel to quantify the linear trends of climate factors and grassland NPP. The equation is listed below:

$$Slope = \frac{n \times \sum_{i=1}^{n} i \times F_i - \left(\sum_{i=1}^{n} i\right)\left(\sum_{i=1}^{n} F_i\right)}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \quad (5)$$

where i is 1 for year 2000, 2 for year 2001, …n, n = 16 as the study period from 2000 to 2015; F_i represents the value of average temperature (GST) and precipitation during the growing season, the actual NPP, and the potential NPP of grassland in time of i, $i = 1, \ldots n$, n = 16. If *Slope* in Eq. (5) is positive, it indicates the increase trend, in comparison to negative value which connotes the decrease trend. The linear trend of climate factors was employed to check if the climate variation has contributed to the grassland expansion and NPP increase over the 16 years.

2.3.5. Distinguishing the role of climate variation and human activities

The changes in grassland NPP, either positive or negative, are induced by climate variation and human activities. The total NPP of grassland in 2000 (NPP_{2000}) can be divided into two parts: NPP of the unmodified grassland in 2000 ($NPP_{unmod2000}$) and the NPP of the converted-out grassland (NPP_{loss}). The unmodified grassland refers to the grassland regions that did not occur land use changes during the 2000–2015 period, and the converted-out grassland denotes the regions where were grassland in 2000 but transformed to other land use types in 2015.

$$NPP_{2000} = NPP_{unmod2000} + NPP_{loss} \quad (6)$$

The total grassland NPP in 2015 (NPP_{2015}) also consisted of two components: the NPP of the unmodified grassland in 2015 ($NPP_{unmod2015}$) and the NPP of the newly developed grassland (NPP_{new}). The newly developed grassland refers to the regions that were other land use types in 2000 but converted to grassland in 2015.

$$NPP_{2015} = NPP_{unmod2015} + NPP_{new} \quad (7)$$

Human activities induced changes in NPP (NPP_{hum}), which includes both the effects of land conversion (NPP_{lc}) and management measures (NPP_{ma}) on NPP, was detected by comparing the difference between actual and potential NPP.

$$NPP_{hum} = NPP_{lc} + NPP_{ma} \quad (8)$$

The NPP_{lc}, which refers to the changes of grassland NPP caused by land conversion, only occur in the newly developed grassland. It could be calculated by subtracting the newly developed NPP with NPP loss caused by grassland conversion to other land-use types and climate variation induced NPP change (NPP_{cnew}) in the newly developed grassland.

$$NPP_{lc} = NPP_{new} - NPP_{loss} - NPP_{cnew} \quad (9)$$

Table 1
The abiotic and biotic characteristics of the field observation sites in the Loess Plateau grassland.

Experiment sites	Location	Altitude (m)	Vegetation type	Soil type	Plant community
Guyuan	106°21′–106°27′E, 36°10′–36°17′N	1800–2000	Typical steppe	Mountain gray-cinnamon	*Stipa grandis*, *Stipa przewalskyi*,
Ansai	109°14′–109°16′E, 36°43′–36°46′N	1000–1300	Typical steppe	Loessial soil, sand loess	*Stipa bungeana*, *Artemisia sacrorum*
Yanchi	107°14′–107°16′E, 37°41′–37°43′N	1300–1500	Desert steppe	Sand loess, gray desert soil	*Cynanchum komarovii*, *Oxytropis aciphylla*

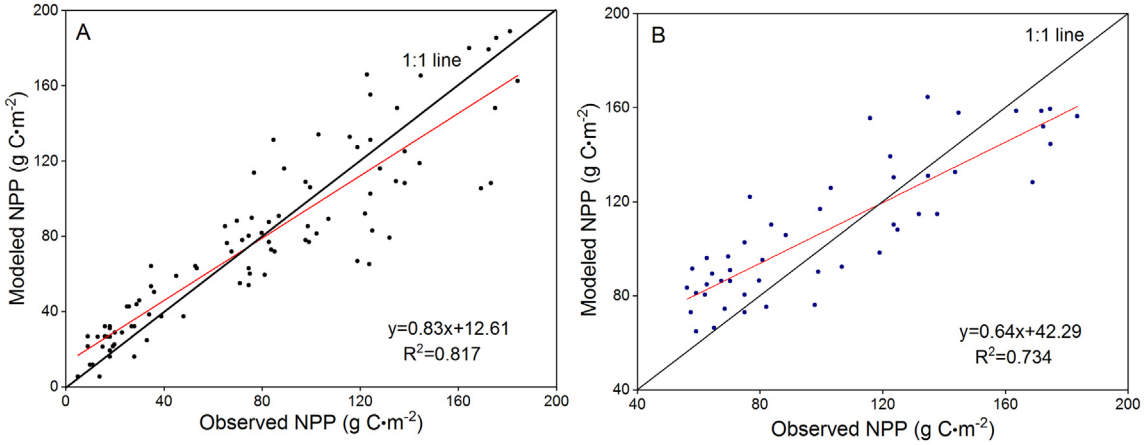

Fig. 2. Validation of actual NPP (A) and potential NPP (B) with field observation data of the Loess Plateau grassland.

Meanwhile, NPP_{ma}, the management measures induced changes to grassland NPP, took place in the unmodified grassland. It was calculated by subtracting NPP of the unmodified grassland in 2015 with the value in 2000 and climate variation induced changes (NPP_{cunmod}) in the unmodified regions.

$$NPP_{ma} = NPP_{unmod2015} - NPP_{unmod2000} - NPP_{cunmod} \quad (10)$$

3. Results

3.1. LUCC of the Loess Plateau grassland

Based on the results, the total area of grassland in the Loess Plateau has experienced a net increase of 0.43 × 10^4 km^2 during the 2000–2015 period (Fig. 3A). A total of 1.09 × 10^4 km^2 of grassland

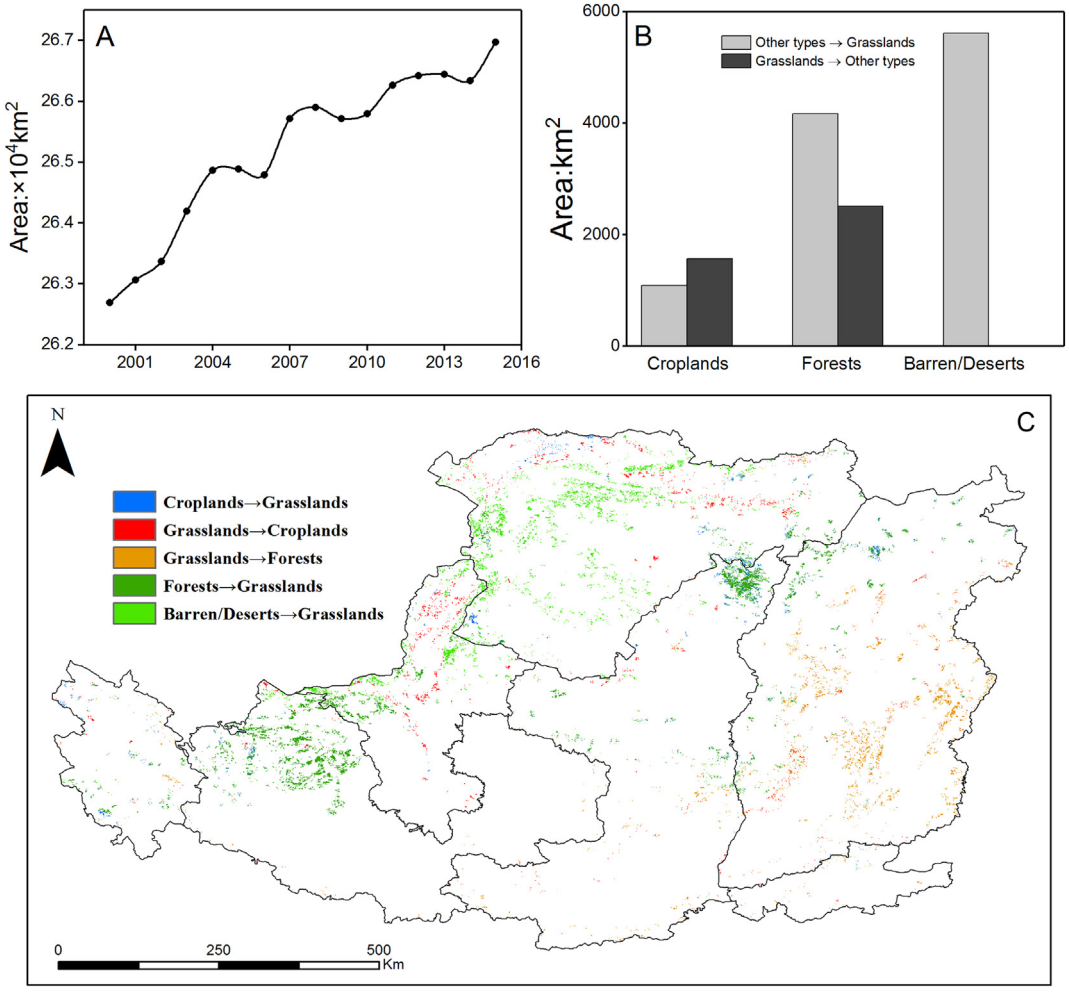

Fig. 3. The temporal dynamics of grassland area (A), areas of main grassland transformation (B) and spatial pattern of main land use changes (C) in the Loess Plateau between 2000 and 2015.

was transformed from all the other land uses, whereas 0.66×10^4 km^2 of grassland was converted to all the other land use types. The newly developed grassland was mainly converted from the croplands, forests, and barren/deserts, accounting for 10.01%, 38.34%, and 51.64% of the total amount of converted-in grassland, respectively. The conversion from grassland to forests contributed to most of the loss of the original grassland (0.25×10^4 km^2). Meanwhile, the area of grassland transformed to croplands accounted for 23.96% of the total area of converted-out grassland (Fig. 3B). In summary, the area of newly developed grassland exceeded that of grassland converted to all the other land uses over the 16 years' period.

Fig. 3C shows the spatial pattern of LUCC of grassland on the Loess Plateau. Geographically, the most obvious variation was the transition from barren/deserts to grassland, which mainly occurred in the transitional zone between grassland and deserts in the northwestern part of the Loess Plateau, including the southern fringe of the Mu Us Sandy Land and in the Hobq Desert. The transformation from forests to grassland mainly took place in the southeastern Gansu, and north of Shaanxi. Meanwhile, a fraction of grassland was converted to croplands in the northern Ningxia, and along the north fringe of Loess Plateau. Regions transformed from grassland to forests generally occurred in interwoven forests and grassland regions in Shanxi.

3.2. The effects of LUCC on grassland NPP

The total grassland NPP increased from 40,193.35 Gg C·yr^{-1} in 2000 to 51,518.48 Gg C·yr^{-1} in 2015 (Table 2). The mean NPP of unmodified grassland increased by 45.25 g C·m^{-2}·yr^{-1} from 2000 to 2015, resulting in an increased total NPP by 11,588.41 Gg C·yr^{-1}. The newly developed grassland had an increase of 1297.76 Gg C·yr^{-1} in total NPP, most of which was attributed to the conversion of other land uses to grassland. The NPP increase due to conversion of croplands and forests to grassland was 123.91 and 636.29 Gg C·yr^{-1}, respectively. Meanwhile, the conversion of grassland to all the other land uses had caused a loss of 1561.04 Gg C·yr^{-1} in total NPP for grassland. Grassland reclamation caused a loss of 359.68 Gg C·yr^{-1} in NPP. The transformation from grassland to forests and other land uses accounted for 47.81% and 29.15% of the total grassland NPP loss, respectively. Therefore, the loss in NPP caused by the conversion of grassland to all the other land use types was greater than the NPP gain resulting from the creation of newly developed grassland. The increase in NPP in the unmodified grassland regions was the primary reason for the increase of overall grassland NPP in the Loess Plateau. The LUCC induced NPP change at the ecosystem scale on the Loess Plateau during the 2000–2015 period are available in the Appendix Table A.1.

Table 2
The mean and total NPP of different forms of grassland conversion in the Loess Plateau between 2000 and 2015.

	Codes	Mean NPP (g C·m^{-2}·yr^{-1})	Area (km^2)	Total NPP (Gg C·yr^{-1})
2000				
Unmodified grassland	22[a]	150.85	256,097.50	38,632.31
Converted-out grassland	21	229.51	1567.17	359.68
in 2000–2015	23	296.81	2514.35	746.28
	2A	185.03	2459.49	455.08
Sum			262,638.51	40,193.35
2015				
Unmodified grassland	22	196.10	256,097.5	50,220.72
Newly developed	12	113.79	1088.92	123.91
grassland in 2000–2015	32	128.94	4169.08	537.56
	A2	113.31	5615.52	636.29
Sum			266,971.02	51,518.48

[a] 22: the unmodified grassland; 21: grassland to croplands; 23: grassland to forests; 2A: grassland to other land use types (including barren/deserts, urban, water/wetlands/ice); 12: croplands to grassland; 32: forests to grassland; A2: other land use types to grassland. Here, the unmodified grassland refers to the grassland regions that did not occur land use changes during the 2000–2015 period. The converted-out grassland denotes the regions where were grassland in 2000 but transformed to other land use types in 2015. The newly developed grassland refers to the regions that were other land use types in 2000 but converted to grassland in 2015.

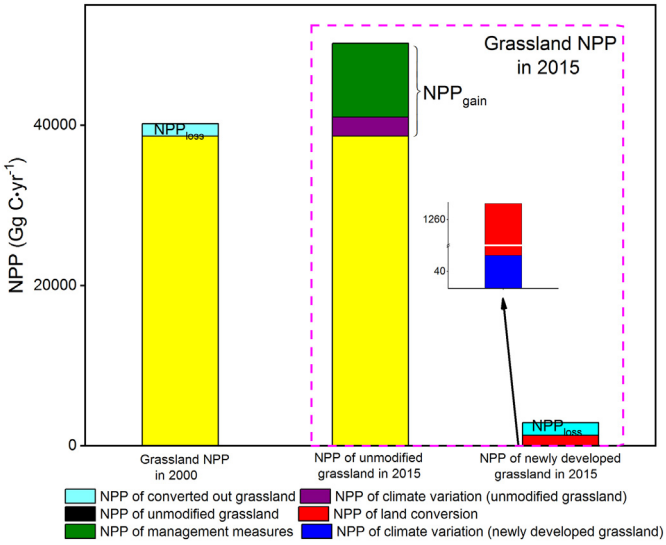

Fig. 4. The total NPP of grassland of the Loess Plateau in 2000 and 2015, and relative contributions of land conversion, management measures and climate variation to grassland NPP change.

3.3. The relative contributions of human activities and climate variation on grassland NPP

Fig. 4 shows the relative contributions of climate variation, land conversion, and management measures to NPP in grassland. Human activities caused an overall increase in the NPP of grassland by 8885.09 Gg C·yr^{-1} from 2000 to 2015. Specifically, management measures promoted an increase in NPP by 9197.97 Gg C·yr^{-1} in the unmodified grassland regions, whereas land conversion caused a loss in NPP of 312.88 Gg C·yr^{-1} in the regions where grassland cover changed (Table 3). Climate variation contributed to the NPP increase over this period, by 49.60 and 2390.44 Gg C·yr^{-1} in the newly developed and unmodified grassland regions, respectively. The gain in NPP resulting from the creation of new grassland was 1248.16 Gg C·yr^{-1} after removing the effects of climate variation induced change. However, the loss of NPP caused by grassland converted to all the other land use types amounted to 1561.04 Gg C·yr^{-1}, indicating that the land conversion had a negative effect on grassland NPP in regions where land cover changed. Therefore, active ecologically-sound management measures

Table 3
Effects of human activities and climate variation on total NPP for different forms of grassland transformation in the Loess Plateau between 2000 and 2015 (Unit: Gg C·yr^{-1}).

Driving forces	Codes	Total NPP (2015)	Climate induced change	Total NPP (2000)	NPP$_{hum}$[b]
Land conversion	Newly developed grassland			Converted-out grassland (NPP$_{loss}$)	
	12	123.91	17.24		
	32	537.56	46.63		
	A2[a]	636.29	−14.27		
	Sum	1297.76	49.60	1561.04	−312.88
Management measures	Unmodified grassland				
	22	50,220.72	2390.44	38,632.31	9197.97

[a] A2 means the conversion from other land use types to grassland.

[b] NPP$_{hum}$ denotes the NPP change caused by human activities. In this study, NPP$_{hum}$ includes both the land conversion induced changes to NPP (NPP$_{hulc}$) in the newly developed grassland and the management measures induced NPP changes (NPP$_{ma}$) in the unmodified grassland.

in the regions of unmodified grassland were the primary driving force for the increase in grassland NPP in the Loess Plateau.

The spatial distribution of the total dynamics of grassland NPP and its driving factors across the Loess Plateau are shown in Fig. 5. Under the combined effects of climate variation and human activities, the overall trend of NPP in grassland increased in the regions from the northeast to the southwest of the Loess Plateau (Fig. 5A). Climate variation was responsible for the increase in NPP observed in the northeastern Loess Plateau; in contrast, climate variation contributed to the decrease in NPP in the northwestern and parts of southwestern regions (Fig. 5B). NPP loss induced by grassland conversion to other land uses mainly scattered in the transitional zones of the grassland, forests and croplands in the mid-west and mid-east region of the Loess Plateau (Fig. 5C). The negative effect of climate variation on NPP in most of regions was alleviated or offset by the management measures in the unmodified regions (Fig. 5D).

4. Discussion

4.1. Effects of climate variation on grassland dynamics

The spatial and temporal variations of GSP and GST during the period of 2000–2015 period are displayed in Fig. 6. Spatially, regions showing increasing GSP were mainly located in the northeastern and southern parts of the Loess Plateau, whereas the decreased GSP was mainly distributed in the southeastern and western regions. The GST decreased over 95.45% of the Loess Plateau. Regions showing increased GST were mainly located in the southeastern and northwestern parts. From a temporal perspective, the GSP rose with fluctuations over the 2000–2015 period and peaked in 2003 (555.45 mm). The GST exhibited an overall decreasing trend from 2000 to 2011, and reached its lowest value in 2012 and then increased afterwards. These variations indicated that the Loess Plateau experienced a wetter and cooler climate during the 2000–2015 period, which agreed with the previous results (Sun et al., 2015).

The descending GST and rising GSP would cause a lower surface evaporation potential and higher soil moisture. As an arid and semi-arid region, precipitation is the dominant climatic factor that affects the growth and expansion of grassland in the Loess Plateau (Xin et al., 2008; Sun et al., 2015). The present study found that climate variation induced an increase in NPP of 2390.44 and 49.6 Gg C·yr^{-1} in the unmodified and newly developed grassland regions, respectively. Therefore, climate variation during the 16-year period helped to the gain in NPP for grassland. The variation in climate should also have benefitted the expansion of grassland to some extent, especially in the central part of the study area. However, the distribution of grassland did not increase in these regions, implying that human activities played a dominant role in the process of changing grassland cover.

4.2. Effects of land conversion on grassland NPP dynamics

Returning deserts and cropland to grassland has caused an increase of 0.67 × 10^4 km^2 in grassland area and 836.42 Gg C·yr^{-1} in grassland NPP. Regions converted from deserts to grassland were mainly located in the western fringe and northwestern part of the Loess Plateau, spanning the northern Ningxia and Inner Mongolia. Previous studies have demonstrated that grassland in these ecologically fragile regions experienced an obvious restoration process during the last decade, such as Mu Us sandy land, Hobq desert, Hunshandak and Horqin sandy land (Jiang et al., 2006; Dai, 2010; Mu et al., 2013). Afforestation and the sowing of grasses have provided efficient methods for restoring degraded environments. According to the data from the Statistical Yearbook of Inner Mongolia, the area of planting grassland increased gradually over the past 16 years, especially after 2009 (Fig. 7A). These actions have successfully stopped the process of grassland desertification and provided

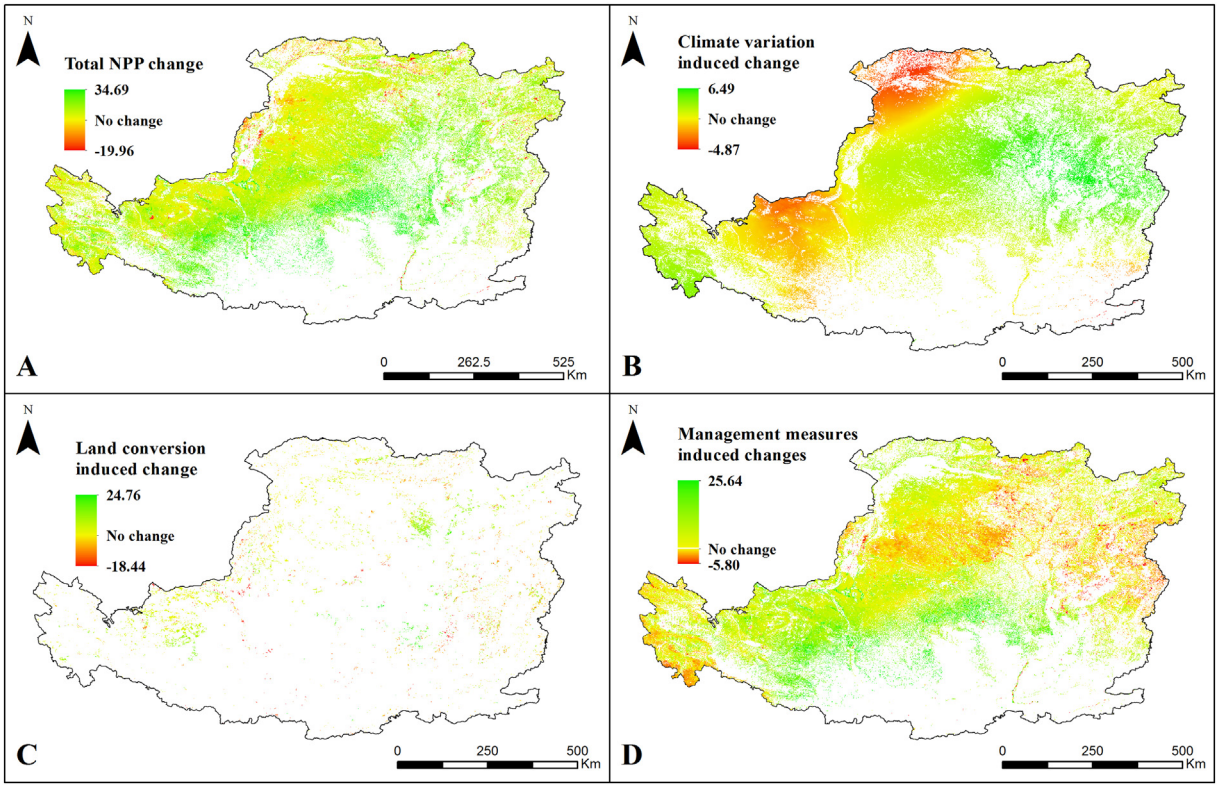

Fig. 5. Effects of land conversion, management measures and climate variation on grassland NPP in the Loess Plateau (Unit: g C·m^{-2}·yr^{-1}). A: total NPP change, B: climate-induced change; C: land conversion-induced change, and D: management measures-induced change.

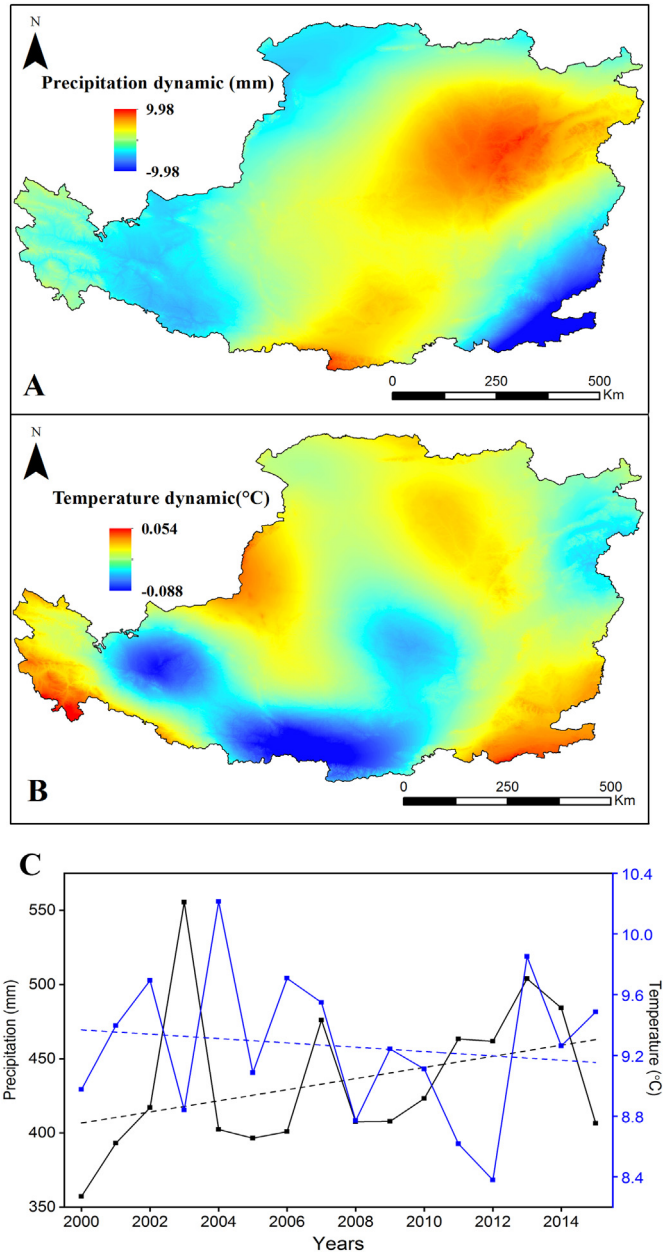

Fig. 6. Spatial pattern of GSP (A) and GST (B) dynamics and their temporal changes (C) in the Loess Plateau from 2000 to 2015.

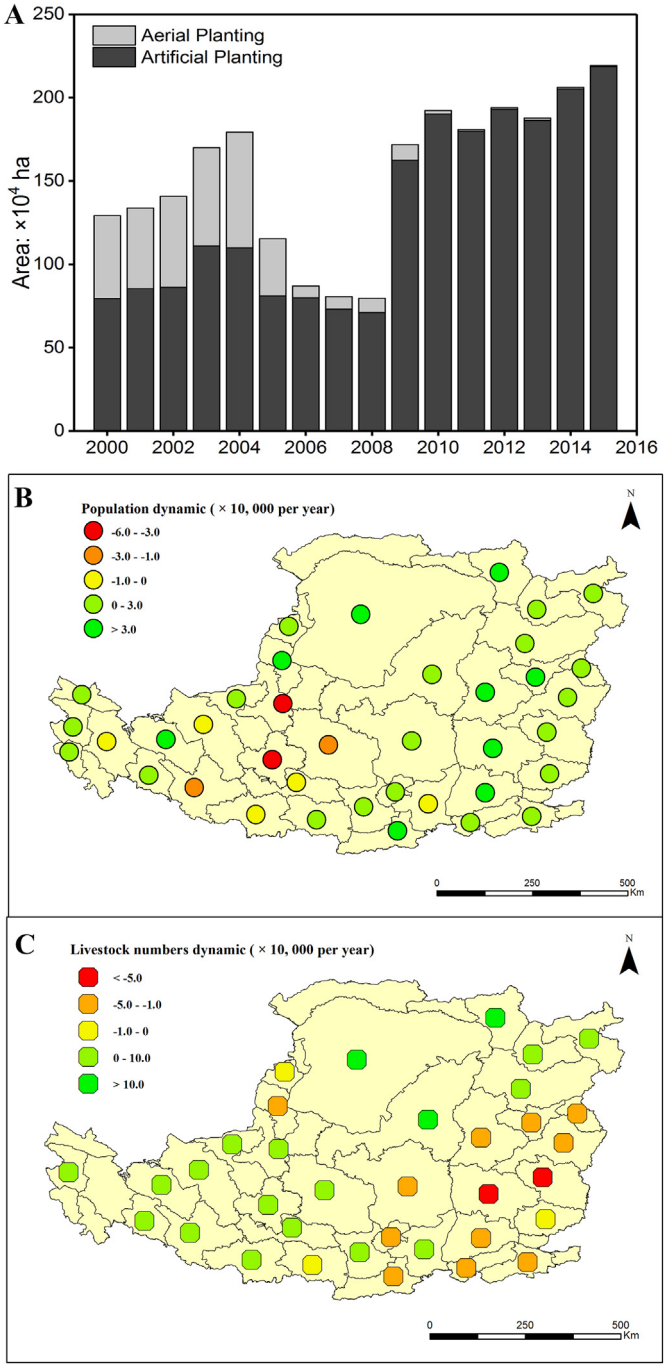

Fig. 7. Area of aerial planting and artificial planting grassland in Inner Mongolia (A), number of population (B) and livestock (C) changes of the main cities in the Loess Plateau between 2000 and 2015. Due to the limitation of data availability, area of planted grassland in other provinces or city level cannot be obtained. The number of population and livestock data were mainly from the statistical yearbook of each city (2000–2015).

a chance for vegetation to regenerate at the oases on the desert edges (Normile, 2007; Chen et al., 2015).

Previous studies have found that land conversion has played a positive role in the expansion of grassland and increase in NPP under the GGP projects (Mu et al., 2013; Zhou et al., 2014). Mu et al. (2013) reported that the area of grassland had a net increase of 77,993 km^2 in the Inner Mongolia during 2001–2009, most of which was attributed to the conversion of deserts and croplands to grassland. The present study reaches the similar conclusions in that the human activities have played a principal role in land conversion in comparison to the climate variation. The difference lies in that land conversion contributes to the grassland NPP increase for the Inner Mongolia, but adds a negative effect to grassland NPP increase for the Loess Plateau. Based on the Statistical Yearbook data of 2000–2015 period, the total numbers of both livestock and human population increased in the Loess Plateau (Fig. 7B and C). The number of human population decreased in the southwestern part of the Loess Plateau, such as in the cities of Wuzhong, Guyuan, and Qingyang, whereas it increased in the other regions. Meanwhile, regions showing a decrease in livestock stocking rates were mainly located in the southeastern part. According to the Fig. 3, 23.96% of grassland was converted to croplands. These regions were mainly located in the Ningxia and Inner Mongolia, where exhibited rising numbers of population and livestock. Meanwhile, the decreased livestock number could probably help to interpret the transition from grassland to forests that concentrated mainly in the Shanxi.

4.3. Effects of management measures on grassland NPP dynamic

Management measures have profound effects on grassland ecosystems (M. Liu et al., 2004). The present study found that the total NPP of unmodified grassland increased by 11,588.41 Gg C·yr^{-1} between 2000 and 2015. The human-induced increase amounted to 9197.97 Gg C·yr^{-1} after subtracting the influence of climate variation, implying the management measures under the ecological projects are the dominant driving forces for grassland NPP increase. Previous studies have demonstrated that the vegetation coverage has increased in the regions of Qinghai, and Shaanxi-Gansu-Ningxia regions under the GGP between 1999 and 2007 (Zhou and Van Rompaey, 2009; Liu et al., 2014). Grazing has also been excluded in most heavily degraded grassland so as to allow native grass species to re-establish, colonize, and succeed (M. Liu et al., 2004). In the loess hilly semiarid grassland of semiarid areas, long-term grazing exclusion significantly improved the species richness, diversity, and productivity of grassland landscape. However, the findings also suggested that the restored grassland should be used by grazing and mowing management after about 15 years' grazing exclusion (Jing et al., 2014; Cheng et al., 2011). For slightly and moderately degraded regions, rotation grazing and seasonal enclosures are superior methods of maintaining the grass community (Shan, 2011; Gao and Liu, 2010). Furthermore, cultivated pasture involving intensive agronomic procedures, such as sowing, irrigating, and fertilizing, have also been adopted in many hilly and gully regions. Reasonless human activities, such as estrepement, denudation, misuse and gouging were banned to retain the restored vegetation. The traditional use of grassland has been shifting from open grazing to the use of feedlots to prevent the destruction of vegetation by livestock. Aridity- and cold-resistant forage is now used for the dry-lot feeding of animals (Guo et al., 2003; Cheng et al., 1995). Enhanced ecological protection and construction with necessary eco-migration should be incorporated in future restoration practices. In addition, drought-resistance shrubs, reasonable configuration of trees-shrubs-grasses and binding interaction of croplands-forests-husbandry should be further developed in the arid and semi-arid regions.

5. Conclusions

The ecological restoration projects of the Loess Plateau have substantially altered the spatial pattern of grassland and NPP from 2000 to 2015. Transformation from forests and barren/deserts contributed major portions to grassland expansion. Despite a certain amount of grassland were converted-out for other land uses, the area of Loess Plateau grassland has a net increase during the study period. The total NPP for Loess Plateau grassland showed an overall ascending trend. Human activities had caused an overall increase in NPP of grassland by 8885.09 Gg C·yr^{-1}. The management measures led to an increase of grassland NPP by 9197.97 Gg C·yr^{-1} in the unmodified grassland, whereas land conversion caused a loss in NPP by 312.88 Gg C·yr^{-1}. Therefore, the management measures in the unmodified grassland regions were the primary driving forces for the increase of grassland NPP in the Loess Plateau. In general, human activities under the ecological programs played a positive role in grassland NPP increase. Admittedly, uncertainties existed in the interpolated climate variables and land use/land cover classification data due to the complex topographic conditions in the Loess Plateau, which may reduce accuracy of modeled results. Nonetheless, this study provides new insight into understanding the impacts of human activities in the grassland restoration process. It is worth noted that the land conversion exerted negative effects in grassland NPP increase. Therefore, related policies should be further adjusted to balance the need for green space and grain trade. Only if these measures were implemented properly, human society, and the natural environment would both benefit from the ecological programs.

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Conflicts of interest

None.

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